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An Optical Filter

The present invention relates to optical filters in the form of optical coatings applied to substrates. The present invention relates particularly, though not exclusively, to optical filters for photovoltaic cells, especially solar cells.

Photovoltaic cells, such as solar cells, typically possess a preferential optical operating spectrum across/within which it is desired to have the photovoltaic cell operate. This may be because the design of the cell causes it to be relatively efficient in respect of, or to be relatively sensitive to, optical radiation within such a preferential spectrum. Alternatively, or additionally, it may be the case that optical radiation outside the operating spectrum is in some way detrimental to the operation of the cell.

For example, the efficiency of the photo-electrical conversion process of many photovoltaic cells falls as the temperature of the cell rises. Consequently, many solar cells employ filters designed to exclude from radiation incident upon the cell those wavelengths of radiation which have a propensity to heat the cell.

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Typically, the filters are designed to reflect incident
Infra-Red (IR) radiation. Other filters designed to
exclude other types of optical radiation, such as Ultra-
Violet (UV) radiation which may be damaging to certain
components of the solar cell, may be employed. These
other filters may be separate from the IR type filters.
Alternatively, a single "band-pass" filter may be
employed which is designed to simultaneously exclude not
only IR radiation but also UV radiation from radiation
incident upon a solar cell, but let "pass" through the
filter optical radiation lying within a spectral band
bounded by the excluded IR and UV radiations.

In general a silicon solar cell is operative responsive
to radiation of wavelengths between 0.40µm to 1.10µm.
Solar energy outside of this band is generally not
converted into electricity and when absorbed only heats
up the solar cell thereby reducing its efficiency.
Certain types of optical band-pass filter comprise a
multi-layer stack structure arranged upon a substrate,
such as a glass substrate. Such multi-layer band-pass
filters are designed to reflect IR radiation (or near-IR
radiation) that lies immediately adjacent one side of a
spectral band of radiation in respect of which a solar
cell is intended to operate (e.g. 0.4µm to 1.1µm
wavelengths), to transmit optical radiation lying within

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that spectral band and to reflect UV lying adjacent the
other side of the spectral band of the solar cell.

The band-pass transmission spectra of such multi-layer
filters is achieved by forming the stack of layers from
repeating pairs of adjacent layers in which any one layer
of a pair is comprised of material having an index of
refraction which differs from the index of refraction of
the other layer of the pair. Thus, the resulting multi-
layer stack has an index of refraction which periodically
jumps between two values as the depth of the multi-layer
stack increases.

As is well known to those skilled in the art, the
"optical thickness" of a layer is given by multiplying
the physical thickness of the layer by the index of
refraction of the material of the layer for a particular
wavelength of optical radiation. Thus, a layer of
constant physical thickness will have an optical
thickness which depends upon the wavelength of optical
radiation passing through it.

By appropriately controlling the physical thickness of
each of the two layers in the repeated pair of layers
such that each has an optical thickness equal to ¼ of a
predetermined optical "design" wavelength (e.g. an IR

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wavelength), the multi-layer stack causes reflection of
optical radiation to occur not only at (and around) the
predetermined "design" wavelength, but also at (and
around) other wavelengths corresponding to "higher order"
frequencies equal to an odd-integer multiple of the
"design" frequency. The result is known as a "¼-wave"
stack, or "interference filter".

Thus, such a quarter-wave stack may be employed as an
optical filter for reflecting IR radiation by selecting
the predetermined wavelength to be a suitable IR
wavelength such that a reflection band is formed adjacent
a desired spectral pass-band. However, a drawback of
such interference filters is that the aforementioned
"higher order" reflection bands often reside well within
the desired spectral pass-band. Thus, such filters may
well reflect radiation which it is not desirable to
reflect.

Other types of multi-stack optical interference filter
have been proposed in which the multi-layer stack is
composed of materials having three different refractive
indices rather than just two. By appropriately arranging
the three different layer types in a repeating pattern
within the stack of layers, the resultant structure is
able to suppress the first few of the offending "higher

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order" reflection bands which usually occur in simple ¼ -

wave stacks as discussed above.

However, a common feature of the simple two-index ¼-wave

stacks and of the aforementioned three-index stacks is

the presence of a discontinuity in refractive index as

between neighbouring stack layers. This discontinuity

arises due to the sudden change in material (and optical

properties thereof) at the interface between adjacent

stack layers. Such discontinuities are detrimental to

the performance and structure of the filter for the

following reasons.

The strength of the multi-layer stack is sensitively

dependent on the degree of interfacial adhesion between

adjacent stack layers. Since adjacent layers in the

aforementioned prior art devices are comprised of

different materials, it is often the case that the

differences (either chemical and/or physical) between

such neighbouring layers reduce the strength of the

interfacial bond which results in the interface being a

primary site of structural weakness in the multi-layer

stack.

Furthermore, in existing interference filters such as

those described above, the transmission spectrum thereof

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at regions in between successive reflection bands are not
uniformly transmissive. That is to say, although the
reflection bands of such interference filters are
generally mainly confined to a limited spectral band,
they are in fact not fully so confined. Rather, the so-
called reflection "bands" often possess significant
ripples or transients of non-zero optical reflectance in
the filter at spectral regions within the pass-band
thereof.

This spreading/dispersion of the reflection band into the
pass-band is principally due to the discontinuity in
refractive index occurring at the interface of successive
layers of a stack. It is detrimental to the transmission
spectrum of such filters since it attenuates optical
radiation which it is intended to pass to an underlying
solar cell. Hence, solar cell efficiency is reduced.

It is an aim of the present invention to overcome at
least some of the aforementioned deficiencies in the
prior art. It is also an aim of the present invention to
permit greater design flexibility when varying the
structure of an optical filter in order to optimise its
performance.

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Accordingly, in a first of its aspects, the present
invention may provide an optical filter including a
substrate having a plurality of layers of materials
stacked upon it each of which layers is formed from one
or both of:

a first material having a first index of refraction; and,

a second material having a second index of refraction
being less than the first index of refraction;

wherein the plurality of layers of materials include a
first layer and a second layer each formed from an
inhomogeneous mixture of said first material and said
second material and a third layer formed from the first
material being stacked in between the first layer and the
second layer wherein the optical thickness of each of
said first and said second layers is greater than the
optical thickness of said third layer.

Due to the inhomogeneous mixing of the first material and
the second material, when forming the first and second
layers, the index of refraction of those layers varies
with the depth of the layer between values greater than
the second index of refraction and less than the first
index of refraction.

Thus, by constructing an interference filter in the form
of a multi-layer stack (on a substrate) comprising a

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repeating group of layers, the group including at least a

relatively high refractive index layer sandwiched

between two layers of varying (but lower) refractive

index, one may for example, provide an interference

filter which substantially reduces or suppresses ripples,

oscillations or transients of non-zero optical

reflectance that would otherwise tend to occur outside

the main reflectance band, and "higher order" reflectance

bands, of the multi-layer stack. That is to say, the

transmission spectrum of the resulting multi-stack filter

will tend to vary substantially more monotonically

within/across the pass-band of the filter, or if not

monotonically then will at least oscillate with lesser

amplitudes therein.

Furthermore, the present invention is able to reduce or

substantially remove any discontinuity in refractive

index and material composition/structure as between

adjacent layers of a multi-layer stack. Consequently,

since a portion of an inhomogeneous layer immediately

adjacent a neighbouring layer is materially very similar

(or identical) to that neighbouring layer, the bonding of

the two layers in question at their interface is enhanced

thereby strengthening the multi-layer structure at that

interface.

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Indeed, it is to be understood that each of the "layers"
of the optical filter of the present invention are formed
from a particular choice of the proportions of the same
two ingredient materials. The term "layer" used herein
therefore refers to strata of differing material
composition occurring in a continuously formed object
whereby each strata corresponds to a particular
composition(s) in the material forming the continuous
object rather than corresponding merely to the
collocation or joining of independent layers.

As will be well known to persons of skill in the art, the
"optical thickness" of a layer of material is given by
multiplying the physical thickness of the layer by the
index of refraction of that layer. For layers of varying
refractive index, the optical thickness is given by
integrating the depth-dependent refractive index across
the depth of the layer in question.

Preferably the optical thickness of the first layer and
of the second layer each differ in magnitude from a value
2Q by less than Q/2, and the optical thickness of the
third layer differs in magnitude from the value Q by less
than Q/2, where Q is the optical thickness of a given
said layer traversed by substantially ¼ of a wavelength

of optical radiation of a common reference wavelength at
which said optical thicknesses are determined.

It has been found that, starting from a basic design
template in which the optical thicknesses of the first,
third and second layers of a stack are respectively as
follows: $(2Q, Q, 2Q)$; one may optimise the performance
of the filter by subsequently varying these three optical
thicknesses during design of the filter and prior to its
manufacture. This variation is, of course, achieved by
varying the physical thickness of the relevant layers
such that the associated optical thickness varies from
the starting value of the basic design template by any
suitable value provided that the variation in the value
of the optical thickness is less than $Q/2$.

For example, the optical thickness of the first layer may
be substantially equal to the optical thickness of the
second layer, or the two said layers may differ in
optical thickness. In either case, the optical thickness
of the first and second layers may or may not be equal in
value to $2Q$ depending upon whether or not design
optimisation requires this.

Alternatively, the optical thickness of the first layer
and of the second layer may each be substantially equal

to the value 2Q. The optical thickness of the third

layer may also be varied when optimising design

performance and may be substantially equal to the value Q

or may differ from that value by an amount less than Q/2.

Preferably the optical filter includes, within its

plurality of layers, a pair of outer layers each being

formed from the first material and between which are

stacked the first, second and third layers. This results

in a five-layer nest including the first, second and

third layers sandwiched between the pair of outer layers.

The optical thickness of each of the outer layers

preferably differs in value from the magnitude Q by less

than Q/2. Thus, the optical thickness of the outer

layers themselves may also individually be varied within

the aforementioned limits in order to assist in

optimising the performance of the filter as a whole. For

example, the optical thickness of each one of the pair of

outer layers may differ from each other or may

substantially equal to each. Where the optical thickness

of each of the outer layers is substantially equal, this

common optical thickness may be equal to Q or may differ

from Q (by less than Q/2).

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It is to be understood that the term "inhomogeneous mixture" in respect of the mixing of materials of differing refractive index, is intended to refer to the nature of the relative proportions of mixed components (which form the mixture) being not homogeneous throughout at least part of the depth of the layer formed by the inhomogeneous mixture. The result of the inhomogeneity of the mixture is a variation of the refractive index of the layer so formed between different depth locations in the same layer.

The index of refraction of the first and/or second layer may vary continuously through at least a part of the depth of the respective layer. Alternatively, or additionally, the index of refraction of the first and/or one second layer may vary substantially in a step-wise manner through at least a part of the depth of the respective layer. In such an arrangement, the first and/or second layer may be a physically continuous article, not being physically discontinuous but having a spatial distribution (inhomogeneous) of mixture which causes sharp/rapid or substantially step-wise changes in the refractive index of the layer at certain regions of depth thereof where the mixture changes correspondingly sharply/rapidly or substantially in a step-wise way (or nearly so).

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All variations in the index of refraction of the first

and/or second layer may occur sharply/rapidly or

substantially in a step-wise manner. In such a case the

first and/or second layer may preferably comprise a

plurality of sub-regions each of which is formed from a

homogeneous mixture of the first material and the second

material whereby the homogeneous mixture forming any one

sub-region differs from the homogeneous mixture forming

immediately neighbouring sub-regions within the

intermediate layer such that the index of refraction of

each of the plurality of sub-regions is substantially

constant through the depth of the sub-region and the

index of refraction of the respective first and/or second

layer varies sharply/rapidly or substantially step-wise

between successive sub-regions thereof.

This amounts to a "digitisation" of the variations in

refractive index of the first/second layer. Once more,

neighbouring sub-regions of the digitised first/second

layer may be physically continuously formed within one

physically continuous respective layer. However, by

suitably controlling the inhomogeneous mixture of the two

materials, one may cause the mixture to change

substantially step-wise between neighbouring sub-regions

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thereby causing a corresponding "step" in the refractive

index therebetween.

In such an arrangement, or in other arrangements, all

variations in the index of refraction of the first and/or

second layer may increase that index of refraction as the

depth of the respective layer increases from regions

thereof remote from the third layer to regions thereof

proximate the third layer. Thus, for example, one may

apply the aforementioned digitisation to a refractive

index "ramp", or may have a smoothly varying refractive

index ramp.

The plurality of layers are preferably arranged to form a

stack of layers in which successive layers are arranged

in a periodically repeating order across the depth of the

stack.

The filter may be arranged to substantially reflect at

least Infra-Red radiation and to transmit optical

radiation at least in the visible optical spectrum. The

filter may be arranged to substantially reflect at least

Infra-Red radiation and Ultra-violet radiation.

The present invention may also provide a cover for a

photovoltaic cell comprising a filter according to the

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first aspect of the invention, and may comprise a

photovoltaic cell comprising such a cover. The

photovoltaic cell is a preferably solar cell.

In a second of its aspects, the present invention may

provide an optical filter including a substrate having a

layer arranged upon it formed from an inhomogeneous

mixture of:

a first material having a first index of refraction;

and,

a second material having a second index of

refraction being less than the first index of refraction;

the inhomogeneous mixture being such that the value of

the index of refraction of the layer oscillates with the

depth of the layer between values greater than the second

index of refraction and less than the first index of

refraction. This may either be an alternative to, or may

form a part of, a multi-layer stack type filter. In the

former case, the oscillating variations in refractive

index result in a filter having one main reflection band

(which may be centred on an IR frequency) and has

substantially no "higher order" type reflection bands.

Since "higher order" reflection bands are suppressed in

such a case, the filter is able to operate as an IR

filter only with little or substantially no reflection of

other wavelengths outside the single reflection band.

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The oscillating variations of the value of the index of
refraction of the layer, according to the invention in
its second aspect, may include at least some sharp/rapid
or substantially step-wise variations, or the variations
may be mostly (or only) such sharp/rapid or substantially
step-wise variations. In such a case the layer may
preferably comprise a plurality of sub-regions each of
which is formed from a homogeneous mixture of the first
material and the second material whereby the homogeneous
mixture forming any one sub-region differs from the
homogeneous mixture forming immediately neighbouring sub-
regions within the layer such that the index of
refraction of each of the plurality of sub-regions is
substantially constant with the depth of the sub-region
and the index of refraction of the layer varies
rapidly/sharply or substantially step-wise between
successive sub-regions thereof.

In this way, the oscillating refractive index of the
layer may be a partially, or wholly, "digitised"
oscillation (e.g. a digitised wave shape) rather than a
continuous oscillation (e.g. wave) as may be the case
alternatively. An optical filter, according to the
second aspect of the present invention, may form a filter
for a photovoltaic cell such as a solar cell. For

example, a solar cell may be formed having an optical

filter comprising only an oscillating (e.g. wave) layer

design (digitised or otherwise) according to the present

invention in its second aspect. Alternatively, such a

wave design could be bounded by other filter layers

within a stack of filter layers according to the

invention in its first aspect. For example, the wave

design may be applied to any one or both of the first and

second inhomogeneously mixed layers of the invention in

its first aspect. Preferably, the wave design includes a

quintic shape comprising one period of a sinusoid

oscillation in the refractive index of a given layer

across the whole width of the layer.

The optical filter, according to either the first or the

second aspect of the present invention and any of their

aforementioned preferred variants or alternatives, may be

for a photovoltaic cell and such as a solar cell.

It will be readily appreciated that the present

invention, in its first and second aspects and according

to any or all of the above variants and preferable

features, implements a method of producing an optical

filter.

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Accordingly, in a third of its aspects, the present

invention may provide a method of producing an optical

filter, the method including:

providing a substrate;

stacking a plurality of layers of materials upon the

substrate each of which layers is formed from one or both

of:

a first material having a first index of refraction; and,

a second material having a second index of refraction

being less than the first index of refraction;

forming a first layer and a second layer of the plurality

of layers from an inhomogeneous mixture of the first

material and the second material;

forming from the first material a third layer of the

plurality of layers being stacked between said first and

second layers;

wherein the optical thickness of each of said first and

second layers is greater than the optical thickness of

said third layer.

Due to the inhomogeneous mixture of the first material

and the second material when forming the first and second

layers, the index of refraction of the first and second

layer varies with the depth of the intermediate layers

between values greater than the second index of

refraction and less than the first index of refraction.

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According to this method, the first layer and the second
layer may each be formed with an optical thickness which
differs in magnitude from the value 2Q by less than Q/2
and the third layer may be formed with an optical
thickness which differs in magnitude from the value Q by
less than Q/2, where Q is the optical thickness of a
given layer traversed by substantially ¼ of a wavelength
of optical radiation of a common reference wavelength at
which the optical thicknesses are determined.

The first layer and second layer may be formed such that
the optical thicknesses thereof differ, or such that the
optical thicknesses thereof are substantially equal in
value. Where the first layer and the second layer are
each formed to have an optical thickness of equal value,
this value may be substantially equal to 2Q, or may be
equal to some other value differing from 2Q by less than
Q/2. The third layer may be formed to have an optical
thickness substantially equal to Q.

The method may include the step of forming a pair of
outerlayers, being part of the plurality of layers, each
being formed from the second material wherein the outer
layers are formed with the first, second and third layers
being stacked between them. The pair of outer layers may

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be formed such that the optical thickness of each such

layer differs in value from the magnitude Q by less than

Q/2. The optical thicknesses of each of the pair of

outer layers may be substantially equal to each other,

and may also be substantially equal to the value Q.

It is to be appreciated that variations in the optical

thickness of one, some or all of the layers of the

optical filter (including the first, second, third and

outer layers) may be varied for the purposes of

optimising the performance of the resultant filter.

Consequently, the method, according to the invention in

its third aspect, may include varying the optical

thickness of one, some or all of the layers in said

plurality of layers for the purpose of optimising the

spectral response of the optical filter for: transmitting

solar radiation within a band of wavelengths to which a

solar cell is operatively designed to be sensitive to,

and, for reflecting solar radiation outwith said band.

According to this method the first and/or second layer

may be formed such that the index of refraction thereof

varies continuously through at least a part of the depth

of the respective layer.

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Alternatively, or additionally the first and/or second
may be formed such that index of refraction thereof
varies substantially in a step-wise manner through at
least a part of the depth of the respective layer.

The first and/or second layer may be formed such that all
variations in the index of refraction thereof occur
substantially in a step-wise manner.

The first and/or second layer may be formed to comprise a
plurality of sub-regions each of which is formed from a
homogeneous mixture of the first material and the second
material whereby the homogeneous mixture forming any one
sub-region differs from the homogeneous mixture forming
immediately neighbouring sub-region within the first
and/or second layer such that the index of refraction of
each of the plurality of sub-regions is substantially
constant with the depth of the sub-region and the index
of refraction of the first and/or second layer varies
substantially step-wise with depth between successive
sub-regions thereof.

The first and/or second layer may be formed such that all
variations in the index of refraction of the respective
layer increase that index of refraction as the depth of

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the layer increases from regions thereof remote from the

third layer to regions thereof proximate the third layer.

The plurality of layers are preferably arranged to form a

stack of layers in which successive layers are arranged

in a periodically repeating order across the depth of the

stack.

The plurality of layers are preferably arranged to

substantially reflect at least Infra-Red radiation and to

transmit optical radiation at least in the visible

optical spectrum.

The plurality of layers may be arranged to substantially

reflect at least Infra-Red radiation and Ultra-violet

radiation.

Non-limiting examples of the present invention shall now

be described with reference to the accompanying drawings

in which:

　　　Figure 1 illustrates a transmission spectrum for a

simple ¼-wave interference-type multi-stack optical

filter, the spectrum comprising a main reflection band,

and a "higher order" reflection band, and reflectance

ripples/oscillations in between;

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Figures 2a, 2b and 2c illustrate the variation in refractive index of a part of a multi-layer stack of an optical filter;

Figure 3 illustrates a transmission spectrum for an interference-type multi-layer stack optical filter employing multi-layer stacks of the form illustrated in Figures 2a, 2b or 2c;

Figure 4 illustrates a multi-layer optical filter comprising a stacked plurality of layer nests each nest being a multi-layer stack of the type illustrated in Figures 2a, 2b or 2c.

Referring to Figure 1 there is illustrated a typical optical transmission spectrum 1 for a simple interference-type (or ¼-wave type) multi-layer stack optical filter of known type comprising a stack of layers of alternate high and low refractive index each layer being of an optical thickness equal to ¼ where λ_0 is a specified "design" wavelength (e.g. $\lambda_0 = 1250nm$). The spectrum illustrates the variation in the optical transmission coefficient (T) of the filter as a function of incident optical radiation wavelength (λ) across a spectral region encompassing the operating bandwidth of a typical solar cell (e.g. from about 400 nm to about 1100 nm in optical wavelength).

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The transmission spectrum 1 has a main broad reflection
band 2 (i.e. low or zero transmission) centred at an
optical wavelength of 1250 nm within the IR region of the
optical spectrum, and a relatively narrow "higher order"
reflection band 3 centred at an optical wavelength of 417
nm (i.e. 417 = 1250/3 approx.) within the blue/violet
region of the optical spectrum and within the operating
bandwidth of the solar cell. This "higher order"
reflection band is the "third order" reflection band, the
"second order" band (at λ = 625mm = 1250/2) being
suppressed and the "first order" band (at λ = 1250nm =
1250/1) being present. A "fourth order" reflection band
(at λ = 312.5nm = 1250/4) is also suppressed.

The transmission spectrum 1 also possesses a series of
optical transmission transients 4 occurring in between
the main "first order" reflection band 2 and the "third
order" reflection band 3, and beyond. These optical
transmission transients 4 cause the transmission
coefficient (T) of the optical filter to repeatedly fall
significantly within the operating bandwidth of the solar
cell. Both the third order reflection band 3 and the
transmission transients 4 are undesirable since they
exclude from use optical radiation which it is intended
that the solar cell receives.

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Figure 4 illustrates an interference-type multi-layer

stack optical filter structure according to the present

invention. The multi-layer optical filter comprises a

multi-layer stack 50 arranged upon a CMG glass substrate

60 about 100µm thick. The multi-layer stack 50 comprises

a series of repeating layer groups (or "nests") each of

which "nests" comprises a first and outer layer formed

from a material (L) having a low refractive index (n). A

succeeding second layer is formed from an inhomogeneous

mixture (M) of the low-index material (L) and a different

material (H) of a relatively high index of refraction.

The second layer has a refractive index (n) which varies

with the layer's depth this being achieved by the

inhomogeneity (with layer depth) of the mixture (M) of

the two materials (L and H) forming the layer. A

succeeding third layer is formed from the high-index

material (H) used in part to form the second layer. A

succeeding fourth layer is formed from an inhomogeneous

mixture (M) of the low-index material (L) and the height

index material (H) such that the refractive index of the

fourth layer varies with the depth thereof as a result of

inhomogeneous mixing of H and L materials. A final fifth

and outer layer is formed from the same material (L) used

to form the first layer.

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Thus, the refractive index profile of the five-layer
"nest" of the stack 50 may be summarised as LMHML as
indicated by the "1st nest" of Figure 4. Each one of the
first, third and fifth layers in the nest has an
"optical" thickness of ¼-wavelength of a predetermined
design wavelength (e.g. λ_0 = 340nm). That is to say, when
optical radiation of the predetermined design wavelength
(λ_0) is propagating through any given one of the first,
third or fifth layers within the nest, the wavelength of
the radiation within that layer (which may differ from
its wavelength as measured in a vacuum) is substantially
four times greater than the layer thickness.

Conversely, each one of the second and fourth layers in
the nest has an optical thickness of ½-wavelength of the
predetermined design wavelength. Consequently, when
optical radiation of the predetermined design wavelength
(λ_0) is propagating through any given one of the second or
fourth layers within the nest, the wavelength of the
radiation within that layer is substantially two times
greater than the layer thickness.

The "2nd nest", and all successive nests, in the stack 50
merely repeat the layering structure of the "1st nest".
In this example seven nests are stacked upon each other,
but fewer or more nests may be so stacked.

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Figure 2 illustrates the refractive index profile of any

one of the multiple five-layer nests illustrated in

Figure 1. The first and fifth layers (the outer layers)

each have the same refractive index, 20 and 24

respectively, which is low (L) and homogeneous across the

depth of the respective layer. The third layer has a

refractive index, 22, which is high (H) and homogeneous

across the depth of the layer.

Intermediate the first and third layer, and intermediate

the third and fifth layers are the second and fourth

layers formed of an inhomogeneous mixture of the

materials used to form the first, third and the fifth

layers, (20, 22 and 24 respectively). The inhomogeneous

mixture of the two materials (L and H) in question

results in a refractive index (21, 23) for the second and

fourth layers respectively which varies continuously with

the depth of the respective layer from the lower

refractive index value (L), through continuously changing

intermediate values to the higher refractive index value

(H), the changing intermediate values being between the

low value (L) associated with the first or fifth layer

and the high value (H) associated with the third layer.

The inhomogeneous second or fourth layer thus has a

ramped refractive index which increases in value from

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regions thereof remote from the third layer to regions

thereof proximate the third layer.

In terms of material types, the five-layer nest structure

may be summarised as: (LMIIML). However, in terms of

layer optical thicknesses the five-layer nest may be

referred to as follows: $(Q, 2Q, Q, 2Q, Q)^n$, where Q

refers to ¼-wavelength of the predetermined design

wavelength (e.g. $\lambda_0 = 340nm$). The integer "n" refers to

the number of times that the nest layer may be repeated

in the optical stack design, in this example n = 7.

It is to be noted that the optical thicknesses of

successive layers illustrated in the designs of Figures

2a, 2b and 2c correspond with what may be termed a

"template" or basic design arrangement which may

subsequently be optimised by varying the optical

thickness of one, some or all of the optical layers in

one, some or all of the nests within a complete optical

filter. It has been found that by varying the optical

thickness of individual layers, or by varying layer

optical thicknesses collectively, one may optimise the

spectral response of the optical filter for the purposes

of transmitting solar radiation within a band of

wavelengths to which, for example, a solar cell is

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operatively designed to be sensitive to, and, for

optimally reflecting solar radiation outwith that band.

It has been found that provided that the optical

thickness of each of the second and fourth layers (being

the inhomogeneously mixed layers) exceeds the optical

thickness of the third (high-index) layer, and where

present the outer (low-index) layers, by less than ⅛ of

the design wavelength (i.e. by less than $\lambda_0/8$) then a

suitable spectral response can be achieved in the optical

filter.

Referring to Figure 3 there is illustrated a transmission

spectrum for a multi-stack optical filter comprising

seven stacked five-layer nests of the form $(Q, 2Q, Q, 2Q,$

$Q)^7$, each nest having a five-layer refractive index

distribution of the form (LMHML) as illustrated in Figure

2a, 2b or 2c. The spectrum of Figure 3 comprises a main

"first order" reflection band centred at a wavelength of

1250nm and a fourth-order reflection band centred at a

wavelength of 312.5nm (i.e. 312.5 = 1250/4). It is to be

noted that the region of the transmission spectrum

intermediate the first order and fourth order reflection

bands enjoys a high level of transmittance in which the

presence of transmittance transients 32 is significantly

suppressed. Furthermore, not only is the second-order

reflection band completely suppressed at a wavelength of

625nm (i.e. 625 = 1250/2), but also the third-order

reflection band 3 centred at 417nm (i.e. 417 = 1250/3) is

suppressed. This is to be compared with Figure 1 in

which simple ¼-wave stacks are unable to suppress the

third-order reflection band at 417nm.

The basic transmission spectrum illustrated in Figure 3

may be further improved by suitably optimising the design

parameters employed in each of the seven nests of the

optical filter with which the spectrum is associated. As

mentioned above, this may involve suitable variations in

the optical thicknesses of one, some or all of the five

layers within each nest. For example, in terms of

optical thicknesses, a nest may be modified to: (1.1Q,

2.3Q, 1.1Q, 2.3Q, 1.1Q). This variation is just one

illustrative example of how relative thicknesses may be

varied, and different variations may be applied to

different nests in the multi-layer stack.

Furthermore, the gradient of the refractive index (i.e.

the variation of refractive index as a function of layer

depth) of one or both of the second and fourth

inhomogeneously mixed layers of a given nest may also be

varied in the procedure for optimising the spectral

response of the filter. An example of this is shown in

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Figure 2b wherein the second layer 25 and the fourth

layer 26 each display a variation in refractive index

which is reduced relative to that illustrated in Figure

2a. In this example each of the inhomogeneously mixed

layers is formed such that the refractive index of the

layer varies from a lower intermediate value (M_1) which is

greater in value than the low refractive index value

associated with the first layer 20, to a second

intermediate value (M_2) greater than the first

intermediate value (M_1) but less than the high-index value

associated with the third layer.

Indeed, it has been found that the mere presence of a

distinctive ramping in the refractive indices of the

second and fourth layer towards the third layer is

sufficient to provide good optimisation of the spectral

response of a filter, while the specifics of each ramp

shape may subsequently be optimised to "fine-tune" the

spectral response.

The form of the refractive index ramp in the second

and/or fourth layers need not be linear, and may be

exponentially increasing (as towards the third layer) or

may be some other more complex ramp shape. Indeed, a

quintic ramp shape may be employed in which the

refractive index of either the second or fourth layer is

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formed so as to gently oscillate over a single sinusoid

period, the quintic oscillation being superimposed upon

an underlying ramp increase in the refractive index.

Figure 2c illustrates a further design variant of the

embodiments described herein, and shows the refractive

index (n) variations of the inhomogeneously mixed second

and fourth layers (27, 28) which vary substantially in a

step-wise manner through the depth of the respective

layer. In this arrangement, the second and fourth layer

(27, 28) are each physically continuous articles, not

being physically discontinuous but having a spatial

distribution (inhomogeneous) of mixture (M) which causes

substantially step-wise changes in the refractive index

of the respective layer at certain sub-regions thereof

where the mixture changes correspondingly substantially

step-wise (or nearly so).

In this variant, the second/fourth layer comprises a

plurality of sub-regions, such as sub-layers 65 and 70 of

Figure 2c, each of which is formed from a homogeneous

mixture of the first material (L) and the second material

(H) over a thickness "x" of the layer. The homogeneous

mixture forming any one sub-region differs from the

homogeneous mixture forming immediately neighbouring sub-

region within the second/fourth layer (M) such that the

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index of refraction of each of the plurality of sub-
regions is substantially constant with the depth "x" of
the sub-region. However, the index of refraction of the
second/fourth layer (M) varies substantially step-wise
between successive sub-regions thereof. This amounts to
a full "digitisation" of the variations in refractive
index of the second and fourth layer.

Once more, it is to be noted that the neighbouring sub-
regions of the digitised second/fourth layers are
physically continuously formed within one physically
continuous respective layer and do not represent
separately formed sub-layers. However, by suitably
controlling the inhomogeneous mixture of the two
materials (L & H), one may cause the mixture to change
substantially step-wise between neighbouring sub-regions
thereby causing a corresponding "step" in the refractive
index therebetween.

The "digitised" inhomogeneous refractive index profile
illustrated in Figure 2c may be applied in place of (or
in addition to) the smoothly varying index ramps of the
second and fourth layers of Figures 2a and 2b. Indeed,
this has been found to be easier to achieve than a
smoothly varying varying refractive index ramp.

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An advantage of such digitisation is that the formation
of such digitised shapes requires less control in the
apparatus used to inhomogeneously mix the two differing
materials employed in the mixture. The need to
continuously regulate/vary the mixture is obviated when
digitisation is employed.

Materials which may be employed in forming the layers of
a multi-layer stack 50 of an optical filter (50, 60)
according to the present invention include Silicon
dioxide (SiO_2 and Hafnium dioxide (HFO_2), and a substrate
glass 60 such as CMG glass.

For example, the following table illustrates an example
of the physical thicknesses of each of the five layers in
a given five-layer nest employed in a multi-nest stack.
The outer first and fifth layers are each formed from
Silicon dioxide, and the third high index layer is formed
from Hafnium dioxide, while the second and fourth
intermediate-index layers are formed from an
inhomogeneous mixture of Silicon dioxide and Hafnium
dioxide. The physical layer thicknesses indicated in the
table below may be translated into optical thicknesses by
multiplying the physical thickness with the refractive
index of the material of the respective layer for the
design wavelength of this example which is $\lambda_0 = 340$ nm.

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The refractive indices at the design wavelength are as

follows:

SiO_2 - 1.46;

HfO_2 - 2.09.

This gives physical thicknesses for the unmixed layers

as:

SiO_2 - 58.2nm;

HfO_2 - 40.6nm,

for a design wavelength of 340nm. The physical thickness

of each ramped layer (layers 2 and 4) of inhomogeneously

mixed materials SiO_2 & HfO_2 is 95.7nm and in this example

the refractive index of each of the two mixed layers

(layers 2 and 4) ramps linearly from an index of 1.46

(adjacent an outer layer 1 or 5) to and index of 2.09

adjacent the high index layer 3.

Layer	Material	Layer thickness(physical) nm
0	CMG GLASS	-
1	SiO_2	58.2
2	SiO_2 & HfO_2	95.7
3	HfO_2	40.6
4	SiO_2 & HfO_2	95.7
5	SiO_2	58.2

The above embodiments are intended to be examples of the

present invention and variants and modifications of those

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embodiments, such as would be readily apparent to the skilled person, are envisaged and may be made without departing from the scope of the present invention.